2018 IEEE 15th International Conference on Wearable and Implantable Body Sensor Networks (BSN)
4-7 March 2018
Las Vegas, Nevada, USA

BiGRA: A Preliminary Bilateral Hand Grip Coordination Rehabilitation Using Home-Based Evaluation System for Stroke Patients

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***Abstract*— Motor impairment is common following stroke. Diminished strength and coordination contribute to reduced ability to perform activities of daily living. The existing healthcare models focus on delivering rehabilitation during the first few months following stroke. Yet, to regain motor control to the greatest degree, rehabilitation should continue across the lifespan. Currently, individuals with stroke are responsible for self-managing their rehabilitation once therapist guided rehabilitation has concluded. Individuals with stroke are frequently given a written home exercise program to help guide their home rehabilitation, but poor compliance demonstrates a better approach is necessary. In this study, we propose *BiGRA*, a novel system to more effectively facilitate in-home bilateral rehabilitation. This system holds merits in: (1) An end-to-end task-oriented system for bilateral grip control which emphasizes the modulation of grip coordination between hands; and (2) Innovative metrics framework to quantitatively analyze the motor control performance. The evaluation shows that *BiGRA* can objectively measure the patients' task performance and is a promising assessment tool for stroke rehabilitation.**

I. Introduction

Stroke is one of the leading causes of disability resulting in impaired self-care, mobility, and cognitive skills [1]. The long-term medical expenses resulting from nursing home, outpatient care and indirect losses associated with lost wages and informal care, brings a great burden to patients and society [2]. It is estimated that total stroke-related cost (direct and indirect) will reach $230.67 billion by 2030 [3]. The importance of post-stroke rehabilitation across the lifespan to improve function is being acknowledged [4].

Precision grip is an indicator of motor performance [5]. Importantly, grip ability in early stages of stroke can be predictive of recovery. The appearance of voluntary grip in the first month following stroke is a good indicator of functional recovery six-months following stroke [6]. Tracking one's ability to grip serves as an effective meter of physical and neurological recovery. Functionally, hemiparesis diminishes accurate force matching in bilateral activities impairing bilateral coordination [7]. Being able to assess and promote recovery of grip are both important post stroke, emphasizing the need for an efficient bilateral hand grip rehabilitation tool.

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Common approaches to home-based rehabilitation include the provision of elastic objects (e.g., theraputty, hand therapy balls and theraband) for unilateral activities as well as a written home program. This approach addresses grip strength, but does little to support grip coordination. Additionally, written home programs frequently have low compliance, with patients reporting boredom [8]. There have been attempts to create more interesting approaches to rehabilitation. Some systems integrate captivating user interface and interactive games [9], but they may also include electromyography requiring more professional assistance. It would be advantageous to provide individuals with stroke a long-term rehabilitation option that is engaging and easy to use. Quantitative feedback can serve as a means to engage individuals offering a method to track performance and help in setting goals for rehabilitation.

To better facilitate grip recovery following stroke, we propose a home-based rehabilitation system, namely *BiGRA* (Bilateral Grip Rehabilitation Assessment). Specifically, *BiGRA* emphasizes hand grip bilateral coordination. It consists affordable hardware and task-oriented software that includes bilateral activities. More importantly, it collects exploitable data and generates quantitative indices to assess motor performance. In the evaluation, we examine differences in grip performance across the lifespan assessing both young and older adults without history of pathology and compare their performance to individuals with stroke. The quantitative metrics selected can distinguish between groups based on grip performance. These analyses provide a method to objectively measure bilateral grip which in turn allows us to track progress in rehabilitation.

To sum up, our main contributions are as follows:

- We developed an end-to-end task-oriented system for effective home-based rehabilitation of grip. The design emphasizes bilateral grip coordination.
- We explored novel quantitative assessment metrics for patients' motor performance in a bilateral grip task.

II. Related Works

Conventionally, grip is examined unilaterally and focuses on maximal grip strength. The Jamar hand dynamometer is one of the most fundamental instruments with mechanical readout kilograms (kg) for grip strength [10]. Force-tracking-task systems in which users unilaterally modulate their grip force to track a waveform are common in research [11], [12]. The analysis from these unilateral systems is more in-depth than the commonly used maximal grip strength,

978-1-5386-1109-8/18/$31.00

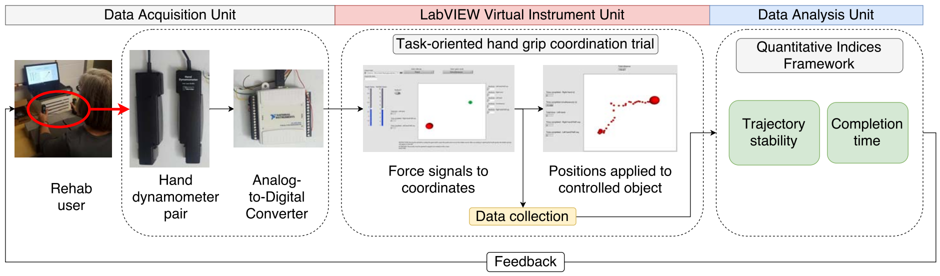


Fig. 1: The framework overview of the hand grip evaluation system.

but is not commonly available to clinicians or patients. There have been some attempts to make this technology available. The GripAble wireless grip rehabilitation system is a commercially available potential solution to unilateral hand grip rehabilitation [13]. Biometrics E-LINK EP9 manages to merge a captivating user interface and interactive games with the hand dynamometer for a more engaging rehabilitation system [9]. However, the use of electromyography suggests a need for greater support from clinicians, making it more difficult to use at home [9]. A limitation to both of these systems is that they do not include bilateral coordination, which is involved in many daily tasks [14]. Other mechanical systems have included bilateral upper extremity rehabilitation [15], however, these systems do not provide quantitative analysis. Overall, existing solutions are not comprehensive enough for home-based stroke bilateral grip rehabilitation.

III. System Overview

The overview flowchart of the system is shown in Fig. 1. The system consists of three main parts: a data acquisition unit consisting of the hardware setup, a LabVIEW Virtual Instrument (VI) unit and a data analysis unit. The hardware contains a pair of force sensors - the hand dynamometers, positioned upright in front of the participant. Signals, which are force values in N, generated by isometrically gripping the force sensors are collected during data acquisition. The normalized signals are assigned as the coordinates of the controlled cursor in the interface, equivalent to moving the cursor on either the x or y coordinate. Detailed analyses of the coordinate and time data are completed at a later time.

Two electrical grip force sensors, known as hand dynamometers, are the main components of the hardware. The pair of hand dynamometers utilized are Vernier HD-BTA (Vernier Software & Technology). They are capable of sensing grip and pinch force between the range of 0-600N. The forces are converted into voltage by the strain-gauge based isometric sensors inside the sensors [16]. For the display of interface and hardware interaction, we utilized the Acer E5-571 (Acer, Inc.).

The analyses provide information on grip coordination and examine strategies that the participant uses to move the cursor to the target. Strategies may include simultaneous or sequential application of force with each hand. For the purpose of this paper, we focus specifically on simultaneous force application, which is equivalent to moving the cursor diagonally.

IV. Evaluation Metrics

A. Completion Time

The most widely used index of the framework is time to complete the assigned task. This is the time that each participant took to complete each trial. The time is recorded from the start of each trial, when a red ball appears, to the moment the participant makes the red ball overlap the green target. Time is measured in seconds. Between trials, participants may rest as long as they choose to avoid fatigue.

B. Optimal Trajectory and S_1 Score

All the participants were directed to control the movement of the ball along a diagonal path to the target. Diagonal movement demonstrates the ability to coordinate simultaneous grip with both hands. As illustrated, our data consists x-y coordinates of the ball over time. Such that, the data stretches from starting point (0, 0) in lower left corner to the upper right corner. The goal is to keep the trajectory as diagonal as possible which requires a good coordination between x-y coordinates and suggests their relationship. For stroke patients we anticipate greater difficulty to coordinate bilateral grip. Compared to healthy young and older adults, we expect individuals with stroke demonstrate greater variation in their path to the target. Thus, it is reasonable to apply nonlinear regression for trajectory analysis. For this study, polynomial regression is utilized.

First, with this method, we can obtain an optimal, smoothed trajectory that has the best fit with all the data points by fitting a polynomial curve. We call this fitting curve **optimal trajectory** which represents the control strategy of the user. Such that, the more a participant can coordinate trajectory in a diagonal pattern, the more overlapping there is between optimal trajectory and actual trajectory. Moreover, beyond the optimal trajectory, we also utilized the nonlinear least squares method to obtain a **trajectory and stability score** or S_1. It's a quantitative index to evaluate how stable the pattern is, a measurement of how well the user can control movement to the target.

The original dataset is captured by LabVIEW as a list of coordinates, (X, Y), to represent the position of the ball at different moments during the exercise. For our polynomial regression model, we used a septic equation. The optimal trajectory, which is the best-fit curve, is function:

$$h(X) = \sum_{i=1}^{m} \sum_{j=1}^{n} \theta_j \times X_i^{j-1} + \varepsilon_i,$$

In the function above, we choose $n = 7$ since $n = 3, 4, 5$ show undesirable representation and $n = 6, 7, 8$ have decent similar performance. θ_j is an assigned parameter, and m is the number of coordinates. For simplicity, we let ε to be zero. In the matrix form, the model becomes:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix} = \begin{bmatrix} 1 & X_1 & X_1^2 & \cdots & X_1^{n-1} \\ 1 & X_2 & X_2^2 & \cdots & X_2^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X_m & X_m^2 & \cdots & X_m^{n-1} \end{bmatrix} \times \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{bmatrix}.$$

Our goal is to find θ to get a function h, such that the least squared error function of h and Y (which is the cost function) is minimal.

$$S_1 = \min(F) = \min\left(\sum_{i=1}^{m}(h(X_i) - Y_i)^2\right),$$

where F is the final cost function. Our goal is to get the final, minimized value of the cost function, which is the trajectory and stability score, or S_1 score. By employing gradient descent, we would be able to find the optimal result for our cost function, which is the value of S_1.

V. Experiment Protocol

A. Participants

This experiment *User Feedback Assessment on Portable Measurement System* was approved by the Institutional Review Board of University at Buffalo [IRB: $030 - 645489$]. The participants in this research project included young adults (YA), older adults (OA), and adults with stroke (AS). The detailed demography of the subjects are demonstrated in Table I.

TABLE I: Demographic table for recruited participants.

		AS	OA	YA
N		6	6	6
Age		63.2 ± 8.89	71.0 ± 8.41	19.7 ± 2.07
Gender	Male	3	2	3
	Female	3	4	3
Max grip (kg)	Right	31.0 ± 13.3	23.2 ± 7.31	42.3 ± 3.44
	Left	12.6 ± 7.54	20.3 ± 7.03	40.6 ± 2.55

B. Protocol

The participants were instructed to sit in front of the system. Their arms were supported by foam blocks and elbow angle was adjusted as necessary to allow them to comfortably hold the hand dynamometers. Ten trials were performed for each participant for them to become familiar with the system. Moreover, the practice trials assisted us to calibrate the sensitivity and size of the red ball and the target in accordance with the participants' motor capability. Sensitivity is a multiplication factor that adds to the original force-to-coordinate signal. With higher sensitivity, the users will need less force to control the red ball. This is crucial for individuals with stroke who have diminished grip strength. Since our goal is to focus on grip coordination, sensitivity has little to no effect on these results. In the next stage, 16 official trials were carried out consecutively with the data recorded automatically to text files for the post-analysis. As mentioned above, each trial required the participant to complete the task of moving the red cursor to overlap the green target in the display. The trial automatically stopped after the red cursor had overlapped the target. Between trials, participants can rest as desired. After the experiment, the participants were asked to provide feedback on the system.

VI. System Validation Results

A. Performance Overview

The shape of the fitting curve determines the overall control strategy. Fig. 2 picks three representative trajectories from each of the groups. The differences between groups are conspicuous if we look into the fitting curves with blue dots. Optimal trajectory of YA subject nearly overlaps the actual pattern along the diagonal route, with minimal number of data points, denoting an easiness in control. To the contrary, the fitting curve of AS show clear peaks and various spreading points. This demonstrates difficulty coordinating movement of the ball to the target.

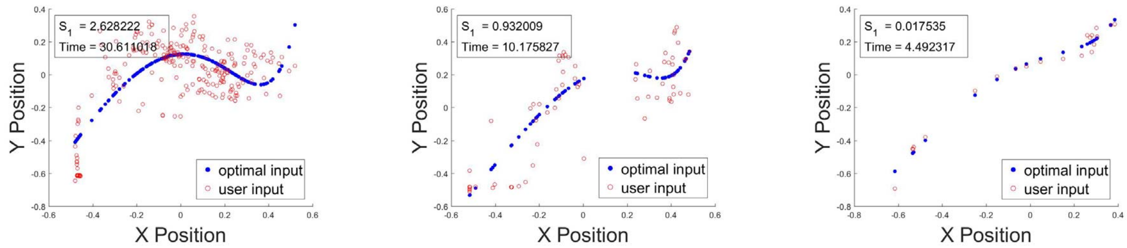
Overall, YA have the most efficient average stability score, of 0.21 ± 0.15 (0.15 is standard deviation), followed by OA without stroke with 0.93 ± 0.90. AS have the least efficient performance with an average S_1 score of 1.97 ± 1.05. The average difference between the groups is shown in Fig. 3(a). This figure shows more variation in AS S_1 score, varying from as low as 0.66 to 3.045, while OA and YA groups are far more consistent. There is a significant difference between YA and AS (p= 0.01 using two-sample t-test). Examining variability, the YA and OA group performed more consistently than the group with stroke. Overall, the YA and OA participants took up to a maximum of 10 and 16 seconds, with the standard deviation of 1.16 and 3.14, respectively. In contrast, the performance of AS was more inconsistent, varying from 10 seconds up to 35 seconds with standard deviation of 9.55. The degree of hand grip impairment for AS could contribute to the variability. The comparative results are illustrated in Fig. 3.

B. Correlation between S_1 Score and Completion Time

These two indices are components of the quantitative framework for assessing user performance. Fig. 4 demonstrates the completion time-to-S_1 score connection for all 18 subjects. This figure suggests that there are overlaps in performance between groups. The overlaps are reasonable, indicating that some subjects have good recovery with nearly normal grip performance. Interestingly, some older adults without stroke are demonstrating scores similar to adults with stroke. Understanding changes in grip with aging is another important line of research as diminished grip is associated with increased mortality [17]. This system is well suited to track changes in motor performance of bilateral grip coordination.

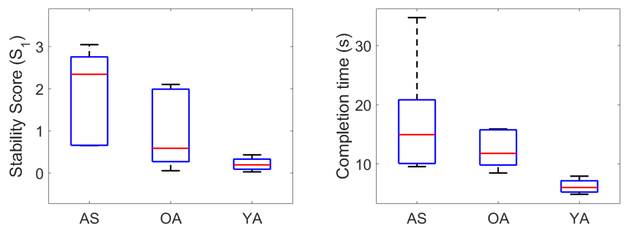
C. Patient Feedback

The questionnaires provided after all experiments reveal positive responses from stroke patients. Two questions were asked: *Would this device would be useful as a tool for home rehabilitation?* and *Would the system be helpful in tracking rehabilitation progress at home?* using a Likert Scale from 1 (strongly disagree) to 5 (strongly agree). The overall rating of the interest on the system is 4.5 over 5 ± 0.504. It shows the potential of enhancing home exercise programs.



(a) AS (b) OA (c) YA

Fig. 2: Comparison of trajectory of representative participants from each group.



(a) (b)

Fig. 3: Box plots of comparison between the control groups (young adults (YA) and older adults (OA) and group with stroke (AS). Both S_1 score (a) and completion time (b) exhibit the same trend - the YA have the most efficient movement to the target whereas the AS have the least efficient movement.

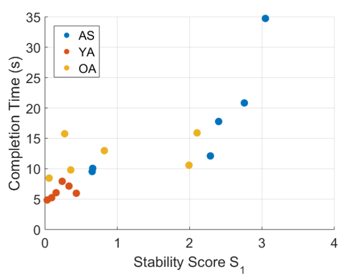


Fig. 4: Span of points from all subjects with respect to the metrices.

VII. Conclusion

In this paper, we presented *BiGRA*, a novel system addressing hand grip recovery post-stroke rehabilitation. The system is portable and can be used for home-based rehabilitation. The system pays particular attention to bilateral hand grip coordination. *BiGRA* is shown to be able to distinguish motor performance differences between different populations with different grip abilities. A portable rehabilitation system for grip recovery that offers the ability to record objective data on grip performance advances the field of rehabilitation. Currently, most individuals with stroke are provided with elastic objects, theraputty or theraballs, and a written home program to strengthen the paretic hand. Our sample population with stroke found *BiGRA* more interesting than their written home programs and enjoyed having objective feedback. The feedback can be used to track progress and assist in setting rehabilitation goals. Further development of this system offers an improved option for long-term home-based bilateral hand grip rehabilitation.

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